Nature Conservation 47: 1–8 (2022)
doi: 10.3897/natureconservation.47.81795
https://natureconservation.pensoft.net

EDITORIAL

A peer-reviewed open-access journal
Nature Conservation
Launched to accelerate biodiversity conservation

Ecological Solutions for Linear Infrastructure Networks: The key to green infrastructure development

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Received 7 February 2022 | Accepted 8 February 2022 | Published 25 March 2022

http://zoobank.org/DC920D21-0948-44F5-A0C0-300E6CE81814

Citation: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (2022) Ecological Solutions for Linear Infrastructure Networks: The key to green infrastructure development. In: Santos S, Grilo C, Shilling F, Bhardwaj M, Papp CR (Eds) Linear Infrastructure Networks with Ecological Solutions. Nature Conservation 47: 1–8. https://doi.org/10.3897/natureconservation.47.81795

Introduction

The rapid expansion of linear infrastructure networks poses a global threat to biodiversity and ecosystem services (Laurance and Balmford 2013; van der Ree et al. 2015). Over the last few decades, research and careful planning have led to solutions which begin mitigating the negative effects of these infrastructures (Lesbarrères and Fahrig 2012; van der Grift et al. 2013; Rytwinski et al. 2016). Transport monitoring protocols

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and data are becoming more widely available, and novel actions are being tested and promoted (Vercayie and Herremans 2015; Schwartz et al. 2020). Robust protocols, landscape genetics, ecological connectivity modeling, remote sensing including GPS animal tracking, among other tools, are being frequently used in infrastructure planning and management (Balkenhol and Waits 2009; Carvalho et al. 2018; Shilling et al. 2020; Valerio et al. 2020; Zeller et al. 2020). The approach towards linear infrastructure planning is also transforming. Linear infrastructure-related habitats are increasingly valued for the biodiversity conservation opportunity they provide and have become a key contributor to Green Infrastructure development (Dániel-Ferreira et al. 2020; Ouédraogo et al. 2020). There is also a growing awareness of the need for coexistence between infrastructure and biodiversity, and citizens participate in this process (Périquet et al. 2018; Waetjen and Shilling 2018).

IENE (Infrastructure & Ecology Network Europe) is a network of experts on linear infrastructures (LI) and biodiversity from Europe and across the world. The main aim of IENE is to provide a platform to promote cross-boundary cooperation in research, mitigation and planning of LI (Seiler and Helldin 2015), facilitated by frequent national and international meetings. IENE organizes an international conference every two years, focusing on biodiversity and transportation (IENE 2021). These conferences provide a way to present innovative research, identify critical questions and problems, discuss ways to increase the efficiency of solutions, and improve communication among decision makers, planners, and researchers. IENE is also a founding member of the Global Congress on Linear Infrastructure and Environment, which brings together experts from every continent to discuss globally important issues of the interaction between linear infrastructure and the environment. Furthermore, IENE, together with other international transport and ecology conference organizations, the World Wide Fund for Nature (WWF) and the International Union for Conservation of Nature (IUCN), has helped to develop The Global Strategy for Ecologically Sustainable Transport and other Linear Infrastructure, a strategy to support biodiversity conservation and enhance ecological connectivity at the governance, policies, planning and implementation stages of transport projects around the world (Georgiadis et al. 2020).

The IENE2020 International Conference "LIFE LINES – Linear Infrastructure Networks with Ecological Solutions" aimed to improve environmental sustainability of infrastructure by bringing together and sharing the experiences of experts involved in the planning, research and administration of linear infrastructures around the world. The Conference focused on transportation infrastructures, but it also included other linear infrastructures, such as electric power lines. The Conference was held online from 12 to 14 January 2021, and was organized by the University of Évora, LIFE LINES project (LIFE14 NAT/PT/001081 https://lifelines.uevora.pt/), and IENE. The Conference was attended by over 300 participants from 31 countries, representing different stakeholders including ecologists, road and linear infrastructure technicians, NGOs, and policymakers. Participations were highly diverse, with 197 presentations, 13 workshops and two side events (LIFE SAFE CROSSING

workshop and LIFE LINES Final Seminar), covering several important topics such as: (1) Innovative Solutions for Linear Infrastructure Impact assessment, Mitigation and Monitoring; (2) Challenges and Opportunities for Infrastructure-Related Habitats; (3) Linear Infrastructure Ecology; (4) Citizen Science and the Involvement of Civil Society; and (5) Legislation and Policy (IENE 2020 Organising and Programme committees, 2021).

About this collection

This Special Issue, entitled "Linear Infrastructure Networks with Ecological Solutions", is a collection of studies that address the main themes of the IENE 2020 conference. Fifteen papers in this volume present research carried out on linear infrastructures, namely roads (8 papers), railways (1 paper), roads and railways (3 papers), power lines (2 papers) and waterways (1 paper). These meaningful contributions were brought from Europe (11 papers), South America (1 paper), North America (2 papers) and Asia (1 paper), and discuss legislation and policy, wildlife-mortality patterns, citizen science, barrier effects, mitigation planning and testing the efficiency of mitigation.

Important insights on **legislation and policy** are highlighted by experiences from Germany and the Carpathians. Steege et al. (2022) present us with a review of projects, political programmes, and progressive legislation on German federal waterways. While, Papp et al. (2022) provide specific recommendations to mainstream ecological connectivity into the planning and design of linear transport infrastructure to maintain the long-term viability of large carnivores in the Carpathians region. These studies contribute with guidance for other authorities striving towards similar goals.

The patterns of **wildlife mortality on roads (roadkill)** were assessed in Brazil, India and Greece. The roadkill of four mammal species were related with landscape use in Brazil. Generalist species such as the crab-eating fox (*Cerdocyon thous*) and the six-banded armadillo (*Euphractus sexcinctus*), showed higher roadkill probabilities in human-modified regions; however, habitat specialist mammals, such as the giant anteater (*Myrmecophaga tridactyla*) and the collared-anteater (*Tamandua tetradactyla*), showed higher roadkill risk with increasing fragmentation of forest or savanna areas, respectively (Cirino et al. 2022). From India, Sur et al. (2022) present the first patterns of vertebrate roadkill assessed in a National Park, demonstrating that roadkill rates were highest during the monsoon season, particularly for amphibians. The analysis of long-term mortality of the brown bear (*Ursus arctos*) in Greece revealed 60% of roadkills were concentrated in four hotspots, occurring most often in periods of increased animal mobility, under poor light conditions and reduced visibility (Psaralexi et al. 2022). All of these results are crucial for identifying the risk to different taxonomic groups, and defining proper mitigation measures specific to each region and communities.

There is an interesting contribution from a **citizen science** project from Belgium, which collected almost 90,000 roadkill records in 12 years. Although collected roadkill data was biased towards larger and more charismatic species, the data suggests that the number of roadkill is decreasing in recent years (Swinnen et al. 2022). This contribution highlights the benefit of getting the public to actively participate in biodiversity conservation.

The role of species behaviour on the **barrier effect of roads** was studied in Portugal. Roads were a behavioural barrier to the movement of small-sized carnivores, although they also take advantage of road proximity as feeding areas (Ferreira et al. 2022). In another study, Fernandes et al. (2022) also found Cabrera voles (*Microtus cabrerae*), an endangered small mammal, had different space use and movement patterns when living on road verges compared to living away from the road. Both studies highlight the need to integrate species behaviour into road permeability projects.

There were also novel approaches to inform **mitigation planning** on roads, railways and powerlines. Helldin (2022) discusses the advantages and disadvantages of single large crossing structures versus several small crossing structures for decreasing barrier effects of roads and railways on wildlife. This debate is of utmost importance as this knowledge improves the efficiency of mitigation planning and the communication between environmental planners and transport agencies. Bird distribution data was used in spatial models to derive a high-resolution map of risks of collisions between birds and power lines across Belgium, identifying locations where mitigation measures should be placed (Paquet et al. 2022). Both of the above approaches can be applied to different contexts, improving spatial planning and design for mitigation across linear infrastructure networks.

The final theme of the papers in this collection focuses on the **effectiveness of mitigation measures,** giving practical recommendations on specific strategies. Accommodating co-use by wildlife and humans may be possible when the mammal species are tolerant of human presence; however, wildlife passages intended to be used by species that are sensitive to human presence should avoid human co-use (Warnock-Juteau et al. 2022). Commonly implemented wire netting fences are not efficient at stopping small animals from climbing over and onto the roadway, thus fences made of alternative materials (e.g., concrete, PVC) may be more efficient (Conan et al. 2022). Short fencing segments can increase the risk of Florida Key deer (*Odocoileus virginianus clavium*) vehicle collisions, especially near fence-ends, thus mitigation measures must be implemented on an appropriate scale to be effective (Huijser and Begley 2022). Wildlife warning reflectors are not an effective method to modify roe deer (*Capreolus capreolus*) behaviour and reduce risk of wildlife-train collisions (Jasińska et al. 2022). Similar results were found from deflectors used to reduce bird-power line collisions (Kornhuber et al. 2022). These authors recommend the use of the animal deflector to a polymeric insulator, since no danger to small birds and small animals could be identified. However, more research and tests on different insulator types need to be conducted before solid recommendations can be made. Testing of mitigation strategies allows for their limitations to be identified and provides a foundation for improving the techniques.

Conference conclusions

The IENE 2020 International Conference presented the impacts and opportunities that Linear Infrastructure brings to nature conservation, allowed the discussion of successes and failures in mitigation and monitoring, and showed novel approaches to harmonize infrastructures and the surrounding environment. The contents of this volume underlines how important ecological solutions are to minimize the negative impacts of Linear Infrastructure and to achieve increasingly greener infrastructures.

Acknowledgements

We wish to thank all colleagues who presented their important work at IENE2020 and to those who also submitted their works to this Special Issue. Thanks to the reviewers for offering their time and constructive suggestions. We additionally thank the Editorial Office of Nature Conservation, and especially to Boriana Ovcharova, the Managing Editor, for their kind assistance during the entire process. We are also grateful to the University of Évora, LIFE LINES project (LIFE14 NAT / PT / 001081), and IENE - Infrastructure and Ecology Network Europe.

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